Laser-based production of metallic conducting paths

Christian Vedder [a], Jochen Stollenwerk [a,b], Konrad Wissenbach [a], Norbert Pirch [a]

[a] *Fraunhofer Institute for Laser Technology ILT, 52074 Aachen, Germany*
[b] *RWTH Aachen University, Chair for the Technology of Optical Systems TOS, 52074 Aachen, Germany*

Abstract

For numerous devices such as OLEDs, solar cells or heated windows conducting paths are needed for collecting or distributing electricity on poorly or non-conducting surfaces. With established techniques the metallic paths can only be produced with a great deal of effort, incurring high costs for plant, equipment and energy. A new laser based process to manufacture conducting paths allows for writing narrow paths (down to 35µm width) of Al, Cu, Ag or similar materials onto flat surfaces of glass (plain or coated with ITO) and silicon wafers by melting and vaporizing a metal foil through optical energy at high speeds of up to 2.5 m/s.

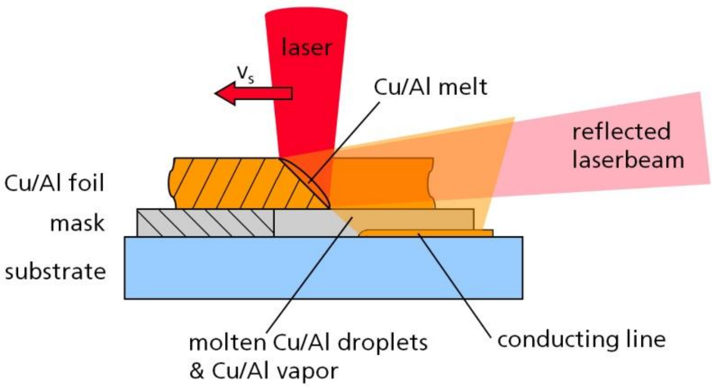
Keywords: Conducting path; laser process; OLED; solar cell; ITO; indium tin oxide; heating wire

1. Motivation

Conducting paths collect and distribute electricity on poorly or non-conducting surfaces of OLEDs, solar cells, heated windows, etc. In most cases the metallic paths can only be produced conventionally with a great deal of effort, incurring high costs for plant, equipment and energy. Electrical conductors in an OLED, for example, are produced substractively – by photolithographic removal of aluminum previously sputtered onto the surface. More than 90% of the material applied in a cost-intensive high-vacuum sputtering process is removed using etchants. To pre-serve the OLED’s homogeneous luminosity, the conducting paths need to be as narrow as possible. This same requirement also applies to solar cells, although less for eye-appeal than for technical reasons: In this case the conducting paths occupy the silicon surface important for the production of electrical energy. They are currently made by screen printing silver pastes which are thermally treated in a furnace process afterwards.

2. Process and Experimental Setup

A mask foil is placed on the substrate which represents the negative of the required conducting path geometry. A donor foil is then attached, providing the material for the conducting path to be produced. This can be aluminum, copper, silver or a similar material (Fig. 1(a)). The assembly is fixed in place and charged with laser radiation along the mask geometry. A mixture of melt droplets and vapor forms, which is transferred from the donor foil onto the substrate (Fig. 1 (b)).



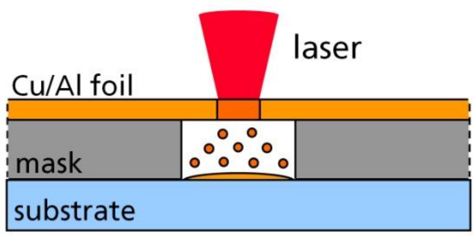


Fig. 1: Scheme of laser-based process, (a) view from side, (b) view from front

Using pulsed laser radiation at 1064 nm with high pulse-to-pulse stability the donor foil is being partly melted and vaporized. This vaporization results in a shock wave departing from the melted surface. It leaves an underpressure at the surface which induces a backward shock wave emitting from the first shock wave front. The second wave is directed to the melted surface and directs molten droplets of the donor foil material onto the substrate[1] (Fig. 2).

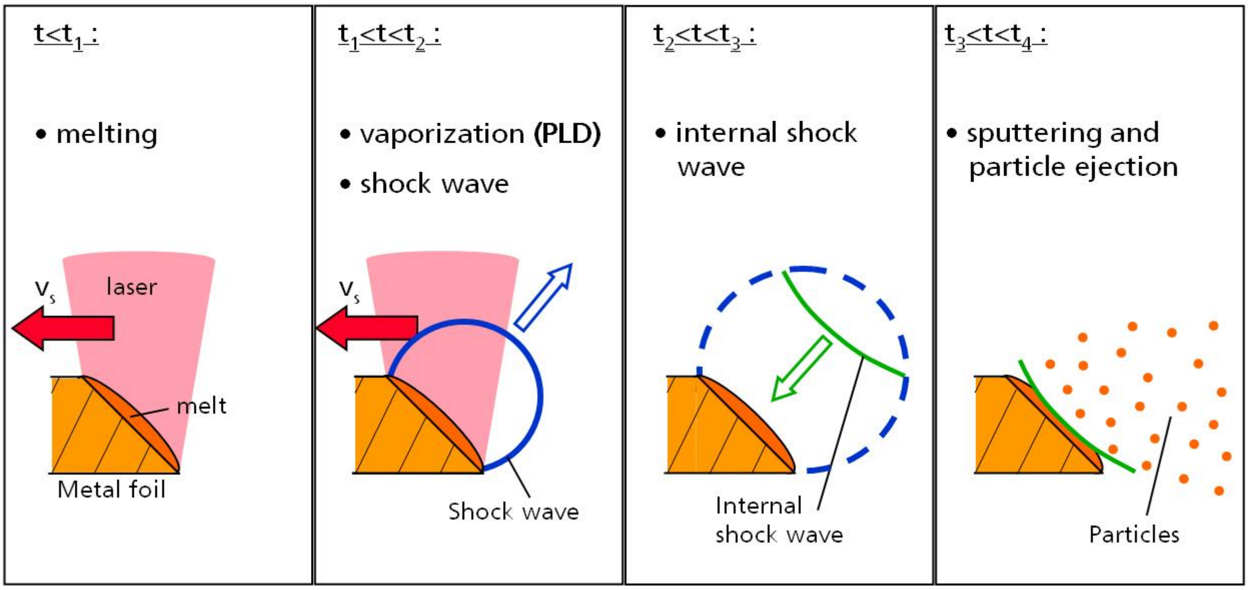


Fig. 2: Scheme of laser-based process in detail[1] (view from side)

Only a part of the particles reaches the substrate. Some particles will be stuck in the mask's slit which leads to a weak adhesion of the foil to the mask. The solidified composite on the substrate forms the conducting path, whose geometry is determined by the mask. Process parameters like donor foil material and thickness, mask thickness, mask slit width, substrate material and surface, etc. and laser parameters like pulse frequency, pulse energy, pulse length, focus diameter, scanning speed etc. are being varied to improve results.

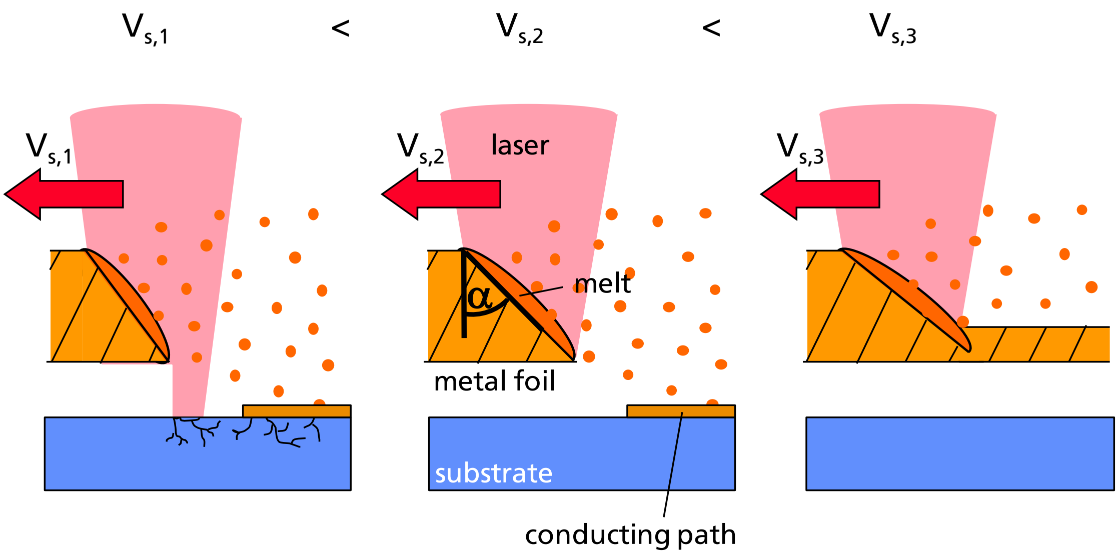


Fig. 3: Schemes of process with different processing speeds ($v_{,s1} < v_{s,2} < v_{s,3}$)

A balanced combination of these parameters leads to the right cutting angle α (Fig.3: $v_{s,2}$) and therefore to the deposition of a conducting path without destructing the substrate. Using a higher processing speed $v_{s,3}$ results in a greater cutting angle: only a part of the metal foil is being melted and evaporated. The metal foil won't be cut through and no material will be deposited onto the substrate. Using a lower processing speed $v_{s,1}$ leads to a smaller cutting angle resulting in a bleed through of laser radiation and for this reason to defects in the substrate's surface.

For the experimental setup a pulsed infrared laser with a wavelength of 1064 nm and high pulse-to-pulse stability is used. The emitted laser radiation is redirected by a scan head with a marking range field of 60 mm by 60 mm. Different substrate types like plain glass, ITO coated glass, pure silicon wafers and solar-ready etched wafers, steel masks and metal foils made of copper and aluminum are used.

3. Results

Figure 4 shows a conducting path made of copper. The path's width is determined by the mask's slit width which in this case is about 110µm. The path's length is about 15mm and has a resistance of about 5.8 Ohms. The path's height varies between 1 and 3.5 µm since the melted metal is being deposited irregularly. The averaged height is about 1.25µm which leads to a sheet resistance of about 0.04 Ohms per square. This suffices for the usage as a conducting path in OLED devices. The conducting path is sharply edged which means that there is no debris around the defined path. In this case the scanning speed is about 1400mm/s which exceeds the processing speed of most competing technologies.

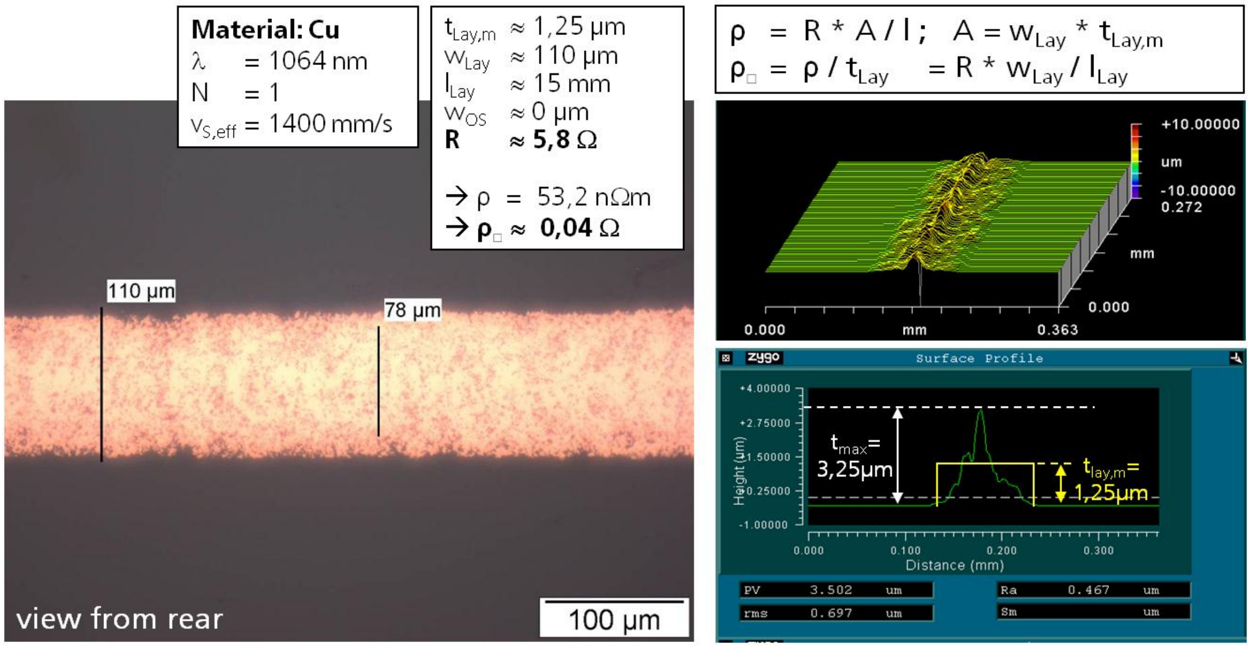


Fig. 4: (a) Microscopic picture of a conducting path on glass made of copper (view from rear), (b) profile of conducting path

Figure 5 shows the achievable processing speed in dependence of pulse repetition rate, laser spot size and metal foil thickness. This leads to the following conclusions:

- The thinner the metal foil d_{Cu}, the higher the achievable processing speed v_s
- The smaller the laser spot size D_s, the higher the achievable processing speed v_s
- The higher the pulse repetition rate f_P, the higher the achievable processing speed v_s (while increasing conducting path resistance until a formation of droplets lead to a non-conducting path)

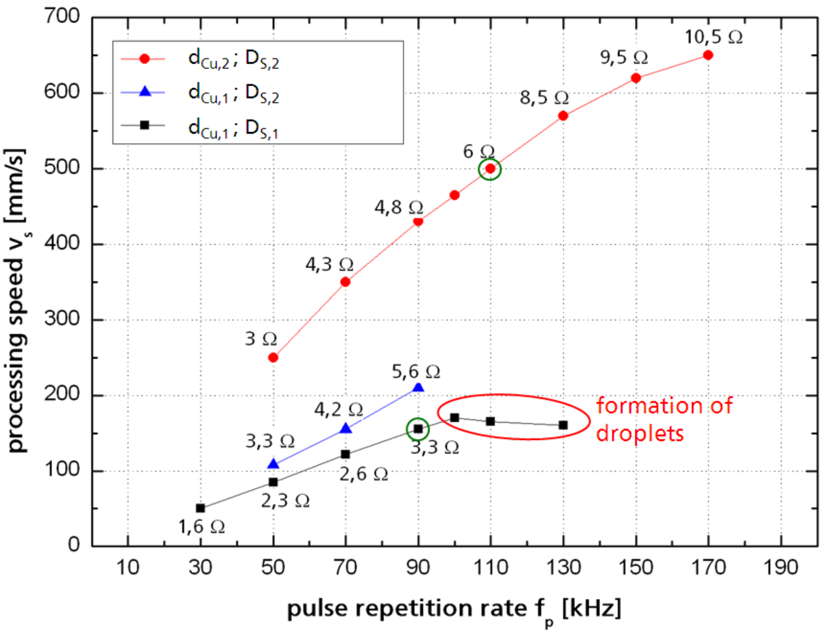


Fig. 5: Achievable processing speeds v_s in dependence of pulse repetition rate f_P, spot size D_s ($D_{S,1} = 2^* D_{S,2}$) and metal foil thickness d_{Cu} ($d_{Cu,1} = 2^* d_{Cu,2}$)

Increasing pulse repetition rate f_p leads to a decrease of pulse energy and an increase of pulse width. This (while adjusting the remaining parameters) results in an increased melting bath and a decreased shockwave leading – at some point – to a formation of single unjoint droplets and thus to a non-conducting path (Fig. 6 (b)).

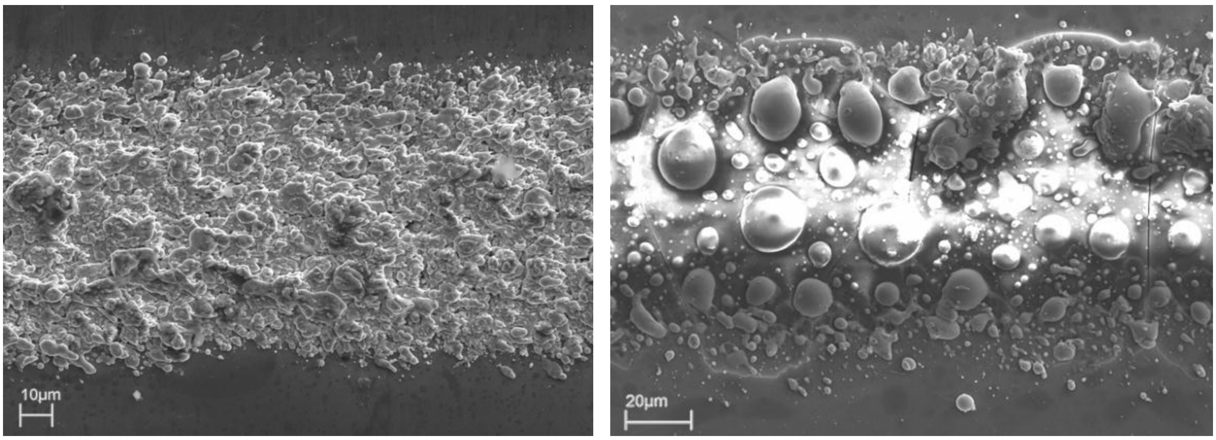


Fig. 6: (a) SEM of a conducting path (copper on glass), (b) SEM of a non-conducting path as a result of droplet formation

Using an even thinner metal foil made of aluminum leads to a further increase of processing speed up to 2.5 m/s (Fig. 7). The higher resistance is due to the fact that the conducting path is 20µm less in width. Like the copper one this path has a sheet resistance of about 0.04 Ohms which suffices for the application in OLED devices.

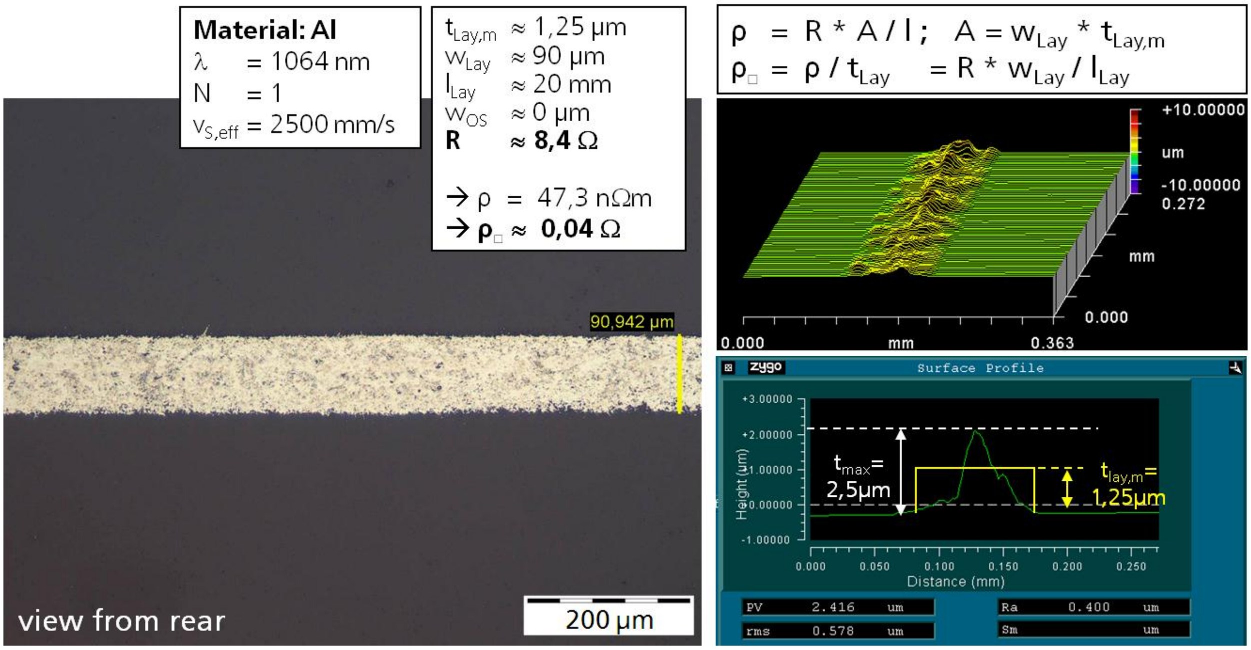


Fig. 7: (a) Microscopic picture of a conducting path on glass made of aluminum (view from rear), (b) profile of conducting path

Depending on the slit width of the mask, conducting paths with widths of 35µm up to 110µm were produced (Fig. 8 (a)). A decrease of resistance R can be achieved by increasing coating repetitions or passes N (Fig. 8 (b)).

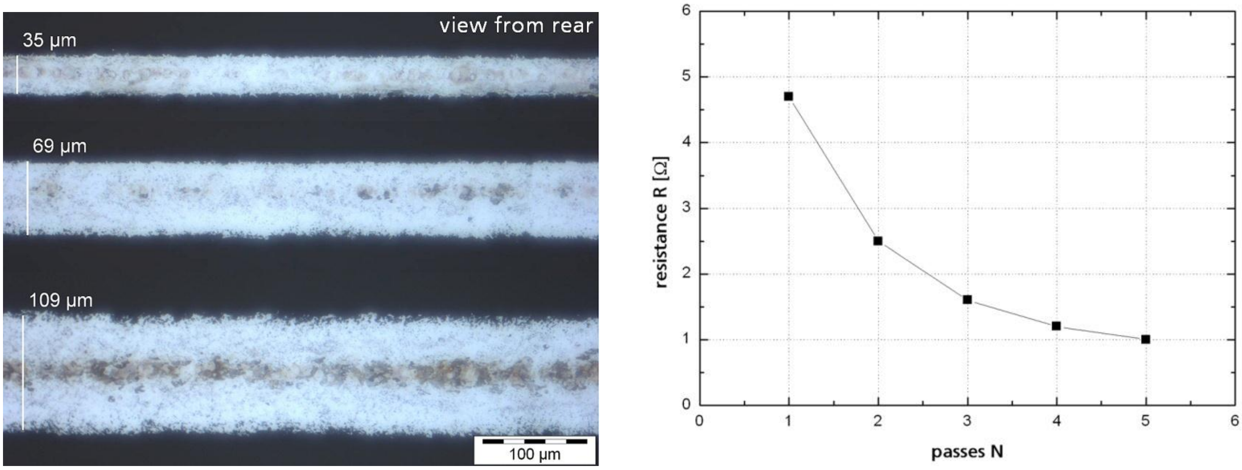


Fig. 8: (a) Microscopic picture of conducting paths of different widths made from aluminum (view from rear), (b) Resistance R of a 15mm long conducting path made of copper in dependence of increasing coating passes N (100µm width)

The process takes place in ambient atmosphere which makes it easy to implement and save costs for high vacuum or inert gas processing chambers. Though a possible danger to increased resistance due to the generation of oxides exists and will be likely. Experiments in an inert gas atmosphere and vacuum show that there are no measurable deviations in resistance to conducting paths made in ambient atmosphere. This can be explained by a bursting of the oxidic membrane surrounding the molten aluminum droplet whilst striking the substrate's surface. The solidified composite will have a thin oxide layer surrounding the conducting path though. Measured contact resistances between ITO layer and conducting path also lie within specifications. Despite all, the laser manufactured conducting path still is porous and holds a specific resistance ($0.0473 * 10^{-4}$ Ohm cm; compare Fig. 7) about 1.8 times higher than bulk aluminum ($0.0265 * 10^{-4}$ Ohm cm). Even overlapping or crossing paths are possible (Fig. 9).

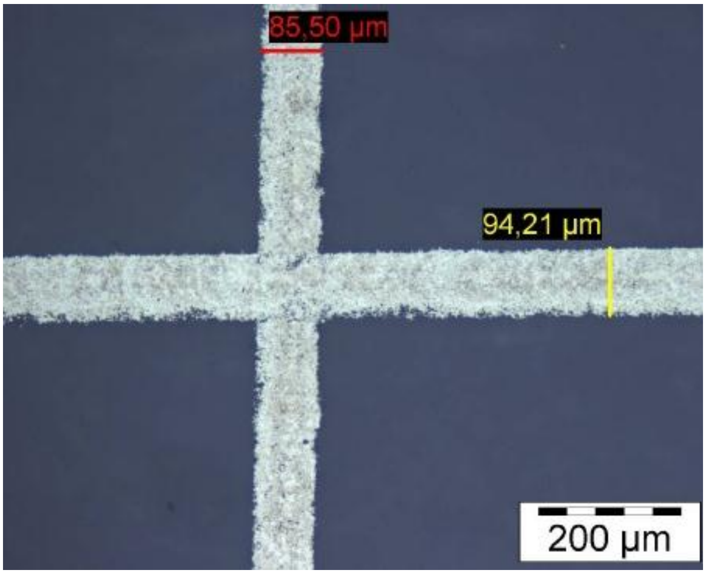


Fig. 9: Crossed conducting paths made of aluminum

The evaluation of adhesion between conducting path and substrate depends on the sort of the path's usage later on. In this case a tape test is being used to reveal adhesion problems. While there are no visual defects of a conducting path made from aluminum on plain glass after the tape test (Fig. 10) one can see some missing path material of a conducting line made from aluminum on ITO coated glass (Fig. 11). This is justified by a poor adhesion of aluminum on ITO in general. Still this result is being judged as sufficient for OLED technology by OLED developing companies.

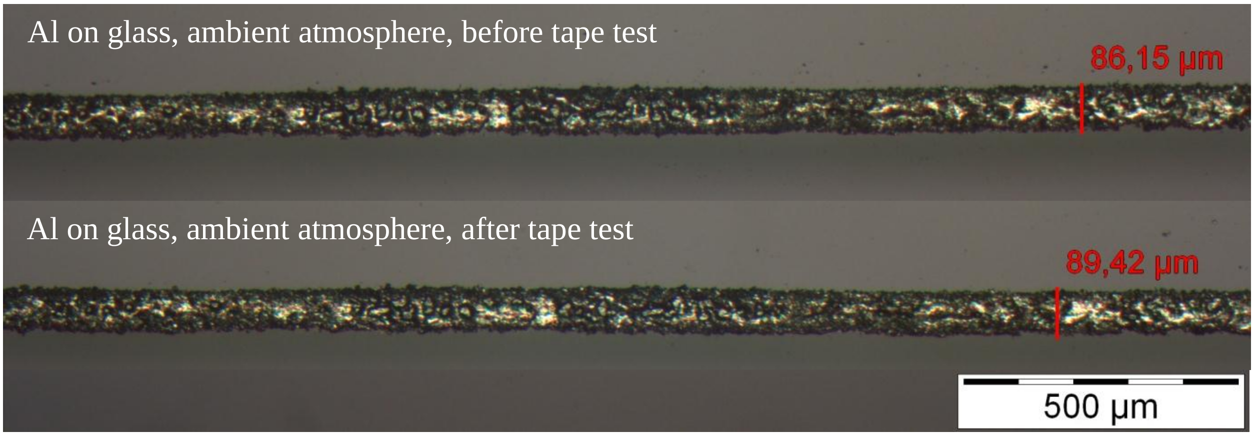


Fig. 10: Microscopic picture of one aluminium conducting path on glass before and after tape test

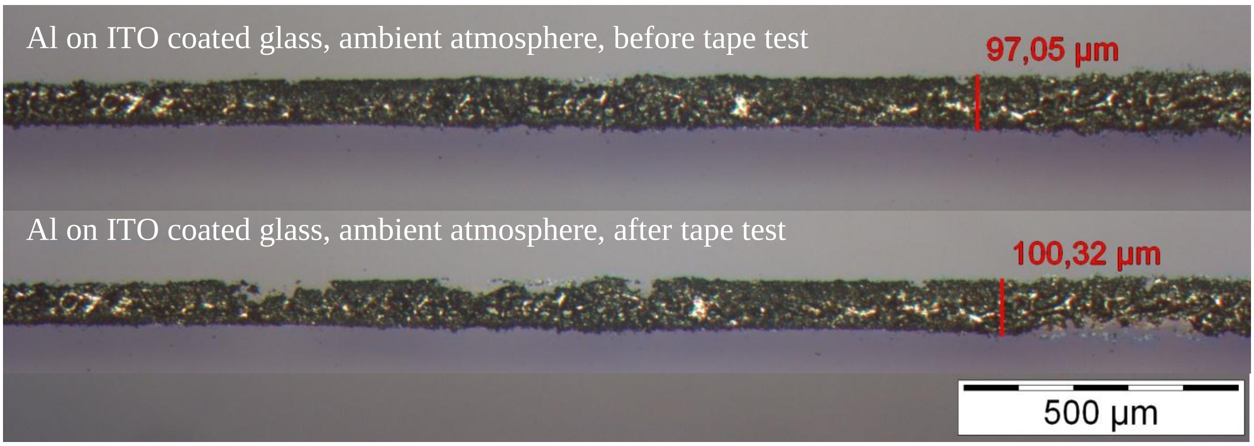


Fig. 11: Microscopic picture of one aluminium conducting path on ITO coated glass before and after tape test

4. Fields of Application and Outlook

Possible applications for the laser-based manufacturing of metallic conducting paths can be OLEDs, solar cells, heated windows etc. Competing technologies like screen-printing are limited to their printing resolution resulting in a conducting path's width that can't be gone below. Also this technology uses expensive silver pastes and a costly furnace process afterwards. With the laser-based process conducting paths can be manufactured that not only are thinner but also reach the same sheet resistance using aluminum in a five-passes-coating (Fig. 12). Even the downstream furnace process can be saved since the laser-manufactured conducting path applies electrical contact to the silicon wafer.

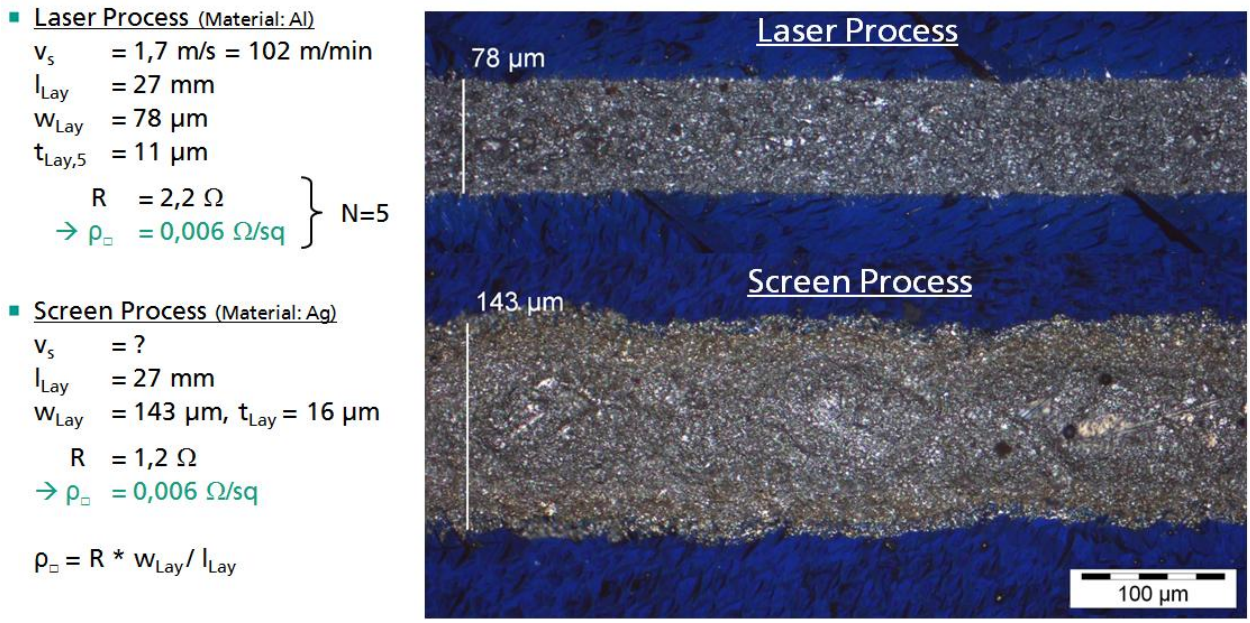


Fig. 12: Comparison of laser and screen-printing process.

OLEDs containing laser-manufactured conducting paths have already been built for research (Fig. 13 (a)). Laser-manufactured conducting paths have also been investigated as wires in heating windows. Figure 13 (b) shows achievable temperatures in dependence of time and current/voltage.

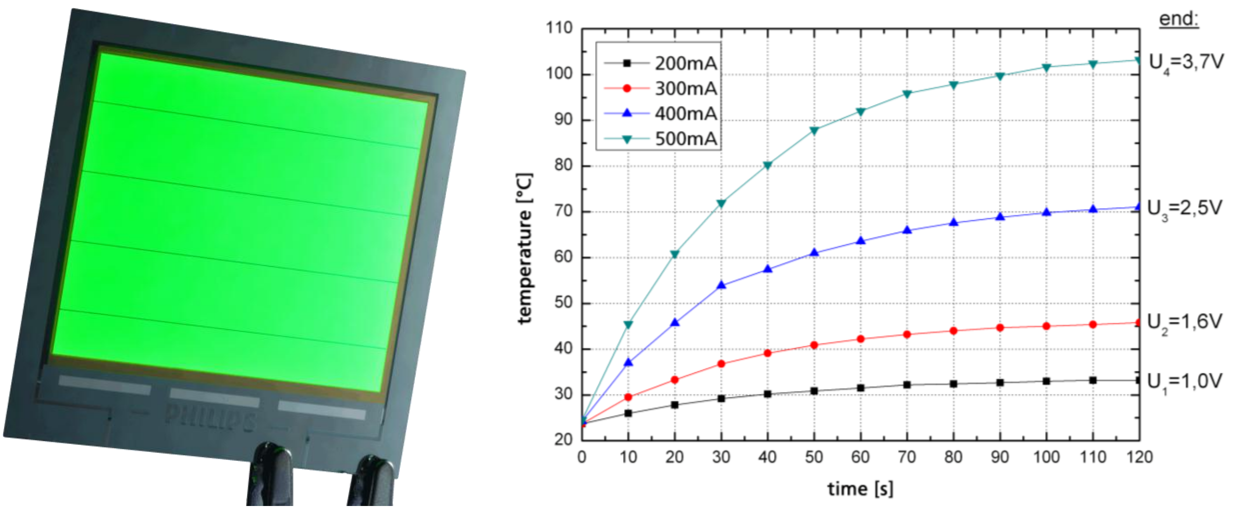


Fig. 13: (a) OLED containing laser-manufactured conducting paths, (b) achieved temperature depending on time and current/voltage of laser-manufactured heating wires

Further steps will be integration of the mask into the metal foil, the implementation of the developed process into an automated industrial in-line process including further improvement of processing speeds and device dimensions and the extension of the metal material palettes (containing Cu, Al and Ag at the moment) and substrate material palette (containing plain glass, ITO coated glass, plain silicon and etched solar wafer).

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